



# Higgs to SUSY Decays at the Full One-Loop Level

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Lake Tahoe, 08/2015

based on collaboration with *C. Schappacher*

1. The Grand Scheme
2. Higgs to chargino/neutralino decays
3. Higgs to Sfermion decays
4. Conclusions

# 1. The Grand Scheme

The LHC up and running ...

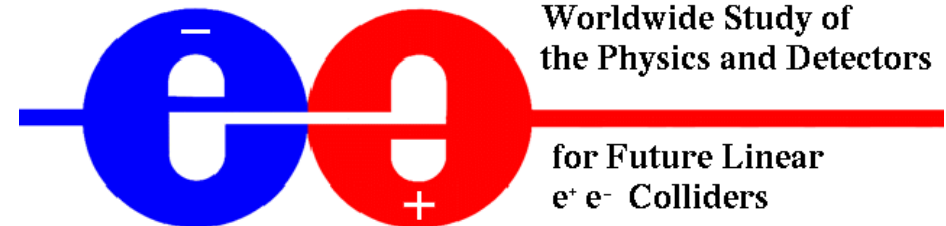
→ discovery of BSM physics this year?



The ILC is still coming ...

... a bit later than anticipated

→ to investigate BSM physics



⇒ New Physics is certainly around the corner

⇒ Time to get ready for BSM physics

The big question:

Which Lagrangian describes the world?

My guess:

It is a supersymmetric one

⇒ concentrate on the MSSM from now on

(other people ⇒ other guesses ⇒ other priorities ⇒ wrong conference?)

In any case:

⇒ we have to measure as many observables as possible

- masses
- branching ratios
- angular distributions
- cross sections
- . . .

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In any case:

⇒ we have to measure as many observables as possible

- masses
- branching ratios
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- . . .

⇒ compare with theory calculations at the same level of accuracy

# The Minimal Supersymmetric Standard Model (MSSM)

## Superpartners for Standard Model particles

$$\begin{array}{llll} [u, d, c, s, t, b]_{L,R} & [e, \mu, \tau]_{L,R} & [\nu_{e,\mu,\tau}]_L & \text{Spin } \frac{1}{2} \\ [\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R} & [\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R} & [\tilde{\nu}_{e,\mu,\tau}]_L & \text{Spin } 0 \\ g & \underbrace{W^\pm, H^\pm}_{\text{Spin } 1} & \underbrace{\gamma, Z, H_1^0, H_2^0}_{\text{Spin } 0} & \text{Spin } 1 / \text{Spin } 0 \\ \tilde{g} & \tilde{\chi}_{1,2}^\pm & \tilde{\chi}_{1,2,3,4}^0 & \text{Spin } \frac{1}{2} \end{array}$$

Enlarged Higgs sector: Two Higgs doublets

⇐ for obvious reasons  
some focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

## Where are we for MSSM Higgs decays?

### 1. Higgs decays to SM

- full 1-loop, leading 2-loop, ... (depending on final state)
- $Z$ -factors at 2-loop

### 2. Higgs decays to SUSY

- mostly 1-loop QCD (depending on final state)
- $Z$ -factors at 2-loop

### 3. SUSY decays to Higgs bosons

- full 1-loop in cMSSM

*[A. Bharucha, T. Fritzsche, S.H., F. v.d. Pahlen, H. Rzehak, C. Schappacer]*

**NEW:** full 1-loop calculation for Higgs decay to SUSY

## Generic problems for SUSY loop calculations:

- SUSY has to be preserved in the calculation
  - Many different mass scales
  - Many more mass scales than free parameters
  - Even more parameters: mixing angles, complex phases
  - Renormalization is much more involved than in the SM
    - much less explored than in the SM
    - has to preserve/respect mass relations
    - depend on mass scales realized in Nature
    - sometimes no really good solution exist (e.g.  $\tan\beta$ )
    - many sectors enter at the same time
- ⇒ this is the biggest issue!



## Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$
$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

physical states:  $h^0, H^0, A^0, H^\pm$

Goldstone bosons:  $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2 (\tan \beta + \cot \beta)$$

## Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$
$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
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physical states:  $h^0, H^0, A^0, H^\pm$

2  $\mathcal{CP}$ -violating phases:  $\xi, \arg(m_{12}) \Rightarrow$  can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_{H^\pm}^2$$

## The Higgs sector of the cMSSM at the loop-level:

Complex parameters enter via loop corrections:

- $\mu$  : Higgsino mass parameter
- $A_{t,b,\tau}$  : trilinear couplings  $\Rightarrow X_{t,b,\tau} = A_{t,b,\tau} - \mu^* \{\cot \beta, \tan \beta\}$  complex
- $M_{1,2}$  : gaugino mass parameter (one phase can be eliminated)
- $M_3$  : gluino mass parameter

$\Rightarrow$  can induce  $\mathcal{CP}$ -violating effects

Result:

$$(A, H, h) \rightarrow (h_3, h_2, h_1)$$

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

$\Rightarrow$  strong changes in Higgs couplings to SM gauge bosons and fermions

## Renormalization summary:

- LHC/LC precision requires all calculations at the per-cent level
- full complex MSSM renormalized  
*[A. Bharucha, T. Fritzsche, T. Hahn, S.H., F.v.d. Pahlen, H. Rzehak, C. Schappacher '11 - '13]*
- stable and well behaved results over nearly complete parameter space
- available as FeynArts model file  
*[T. Fritzsche, T. Hahn, S.H., F.v.d. Pahlen, H. Rzehak, C. Schappacher '13]*
- full one-loop calculations possible with FeynArts/FormCalc/LoopTools
- set-up includes full one-loop corrections (hard/soft QED/QCD radiation)

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⇒ **go and make your prediction!**

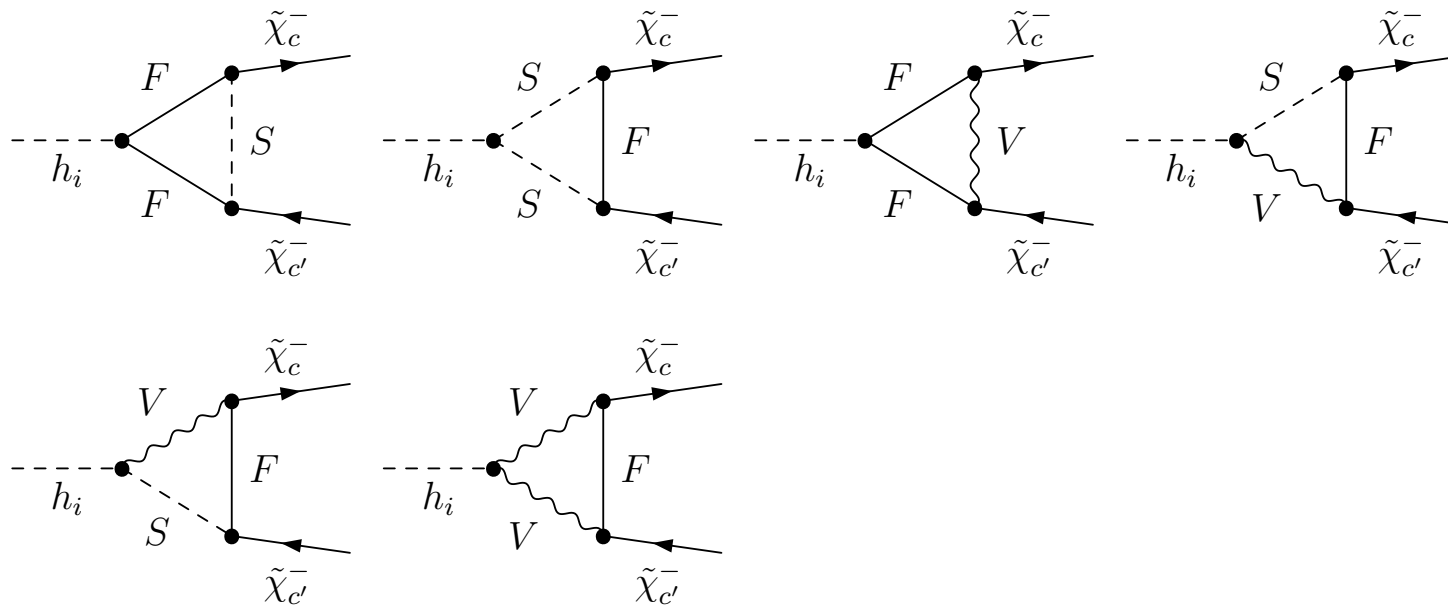
## 2. Higgs decays to charginos/neutralinos

[arXiv:1503.02996]

$$\Gamma(h_i \rightarrow \tilde{\chi}_c^- \tilde{\chi}_{c'}^+) \quad (i = 1, 2, 3; c, c' = 1, 2)$$

$$\Gamma(h_i \rightarrow \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0) \quad (i = 1, 2, 3; n, n' = 1, 2, 3, 4)$$

$$\Gamma(H^\pm \rightarrow \tilde{\chi}_n^0 \tilde{\chi}_c^\pm) \quad (n = 1, 2, 3, 4; c = 1, 2)$$



## Numerical example scenario:

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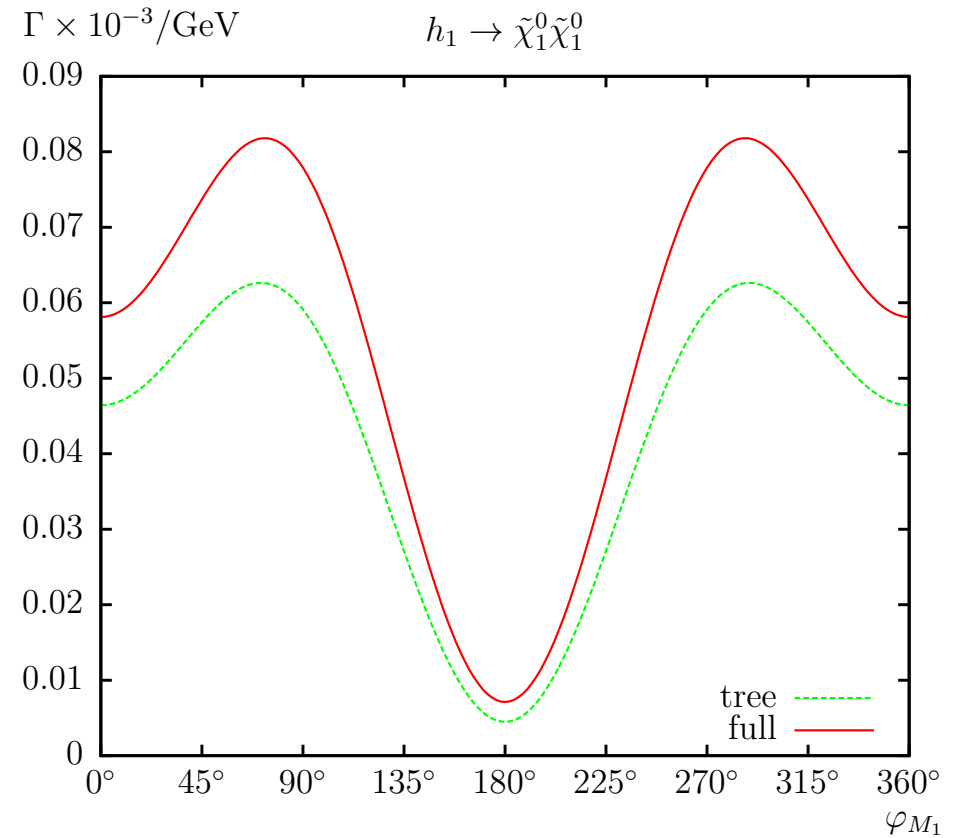
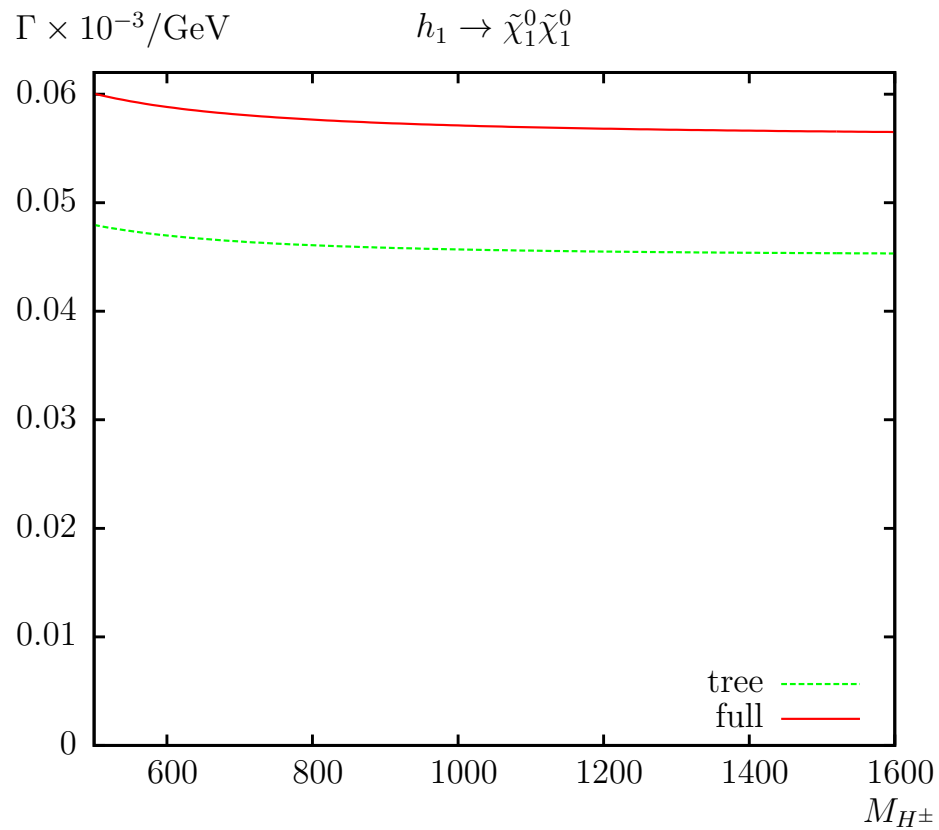
$\tan \beta$	$\mu$	$A_{u_g}$	$A_{d_g}$	$A_{e_g}$	$ M_1 $	$M_2$	$M_3$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_2}$	$m_{\tilde{\nu}_\tau}$	$m_{\tilde{\tau}_1}$
10	500	1200	600	1000	300	600	1500	394	771	582	280	309

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Parameters varied:  $M_{H^\pm}$ ,  $M_1$ ,  $\varphi_{M_1}$

- in agreement with exp. data
- opens up many (all) decay channels
- relevant parameters varied
- . . .

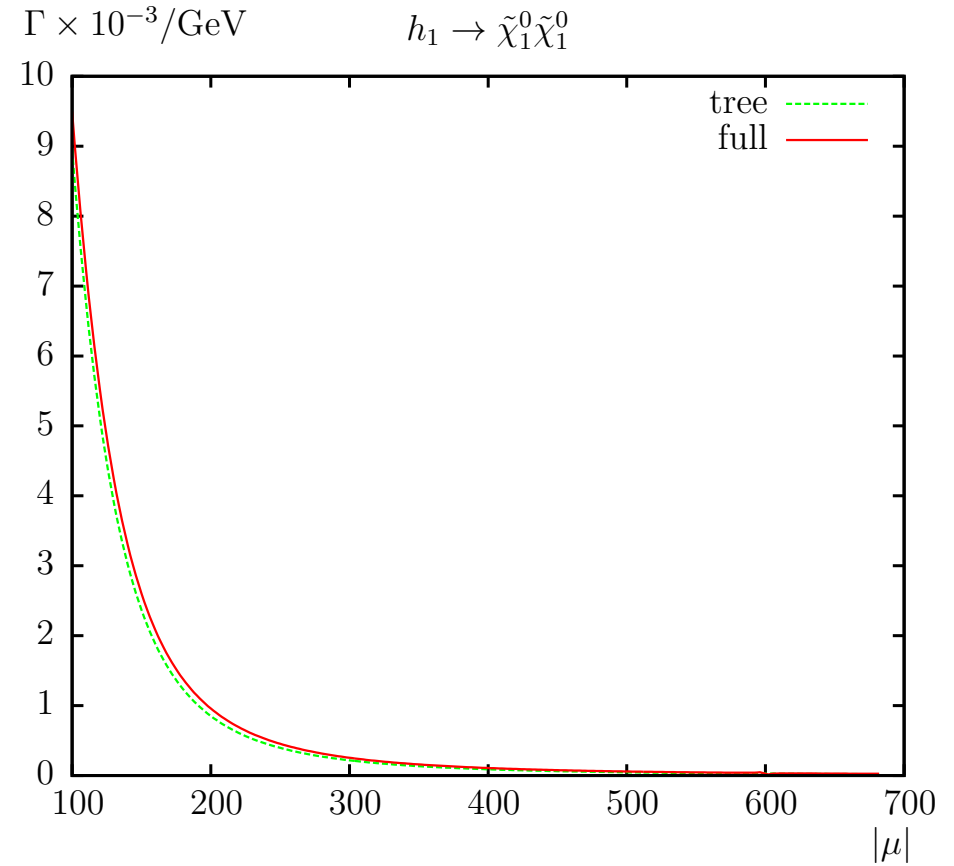
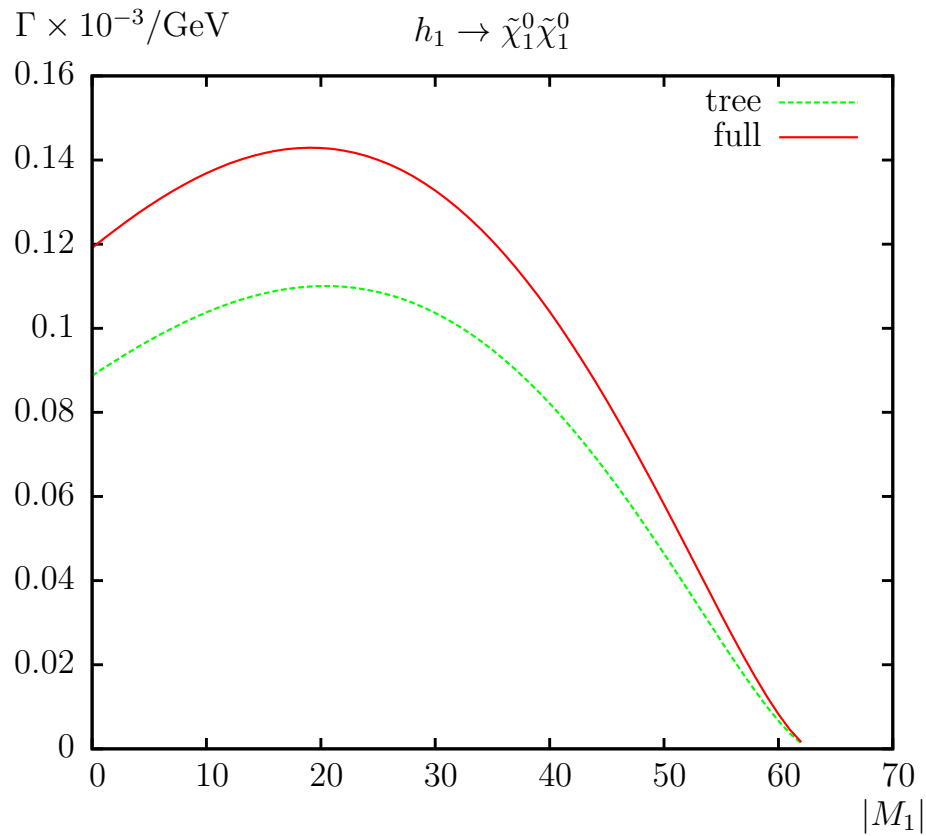
## Light Higgs decay to Dark Matter (I):



- ⇒ loop corrections  $\sim 20\%$
- ⇒ strong phase dependence

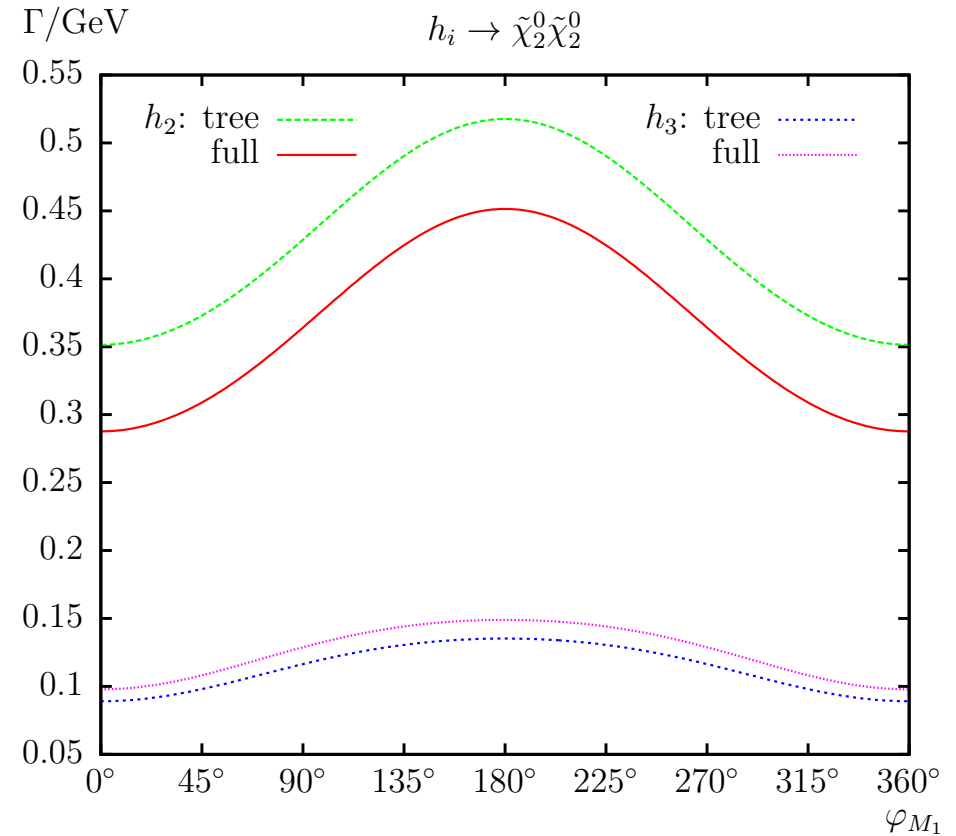
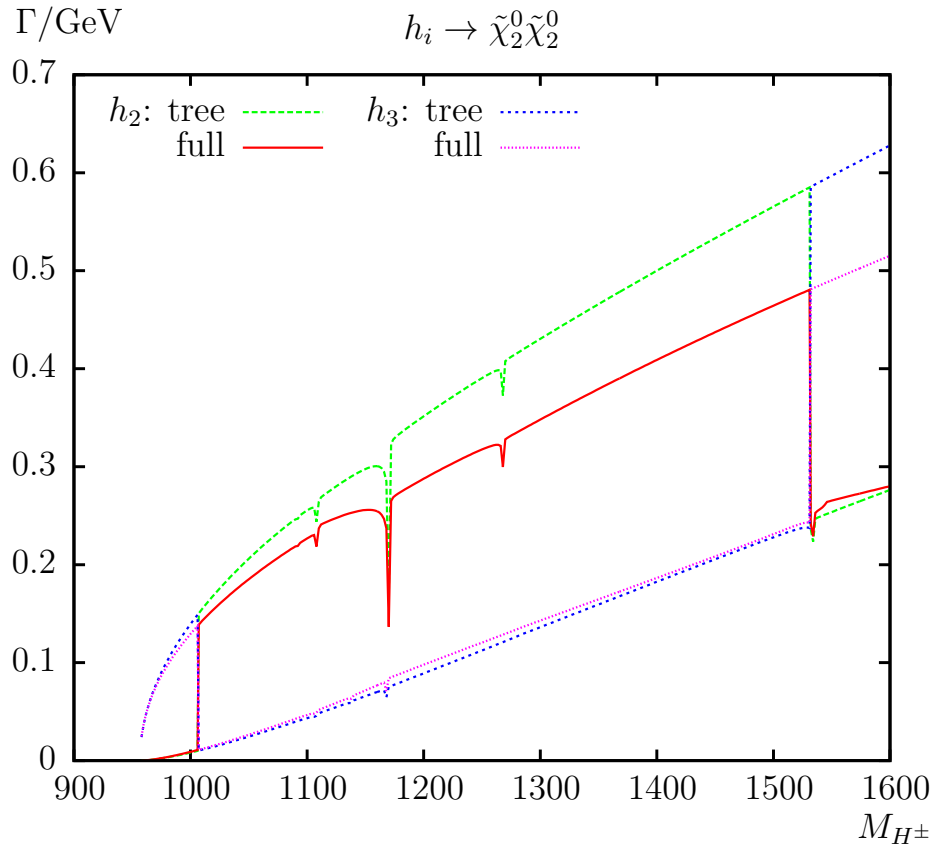


## Light Higgs decay to Dark Matter (II):



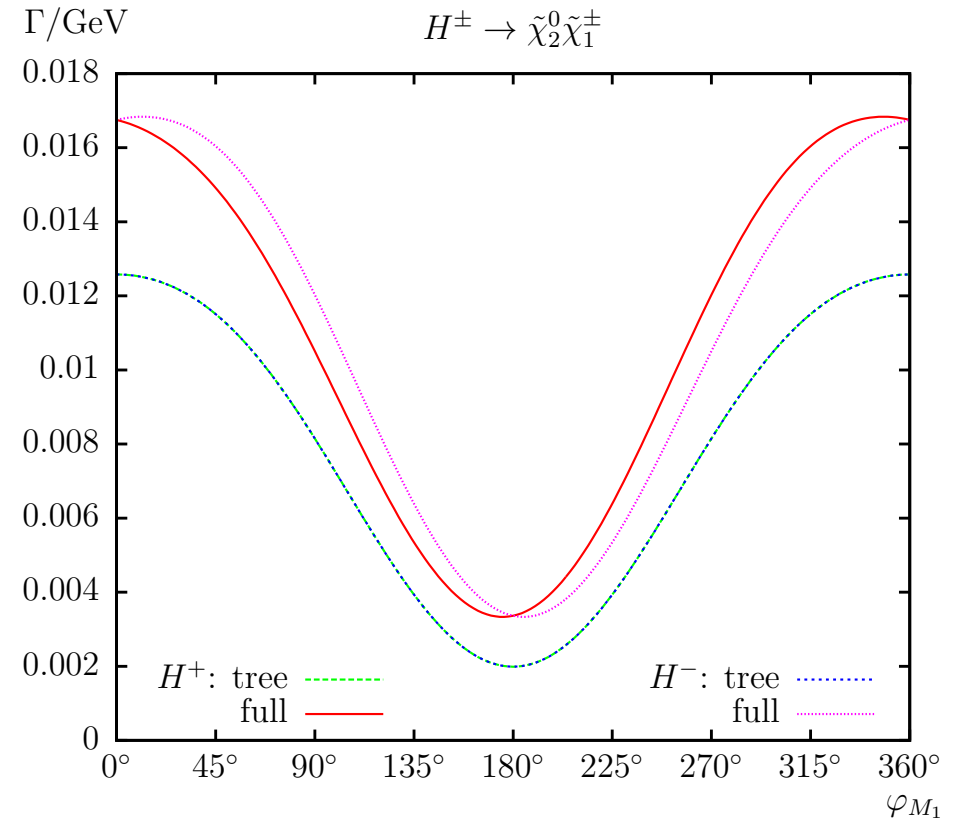
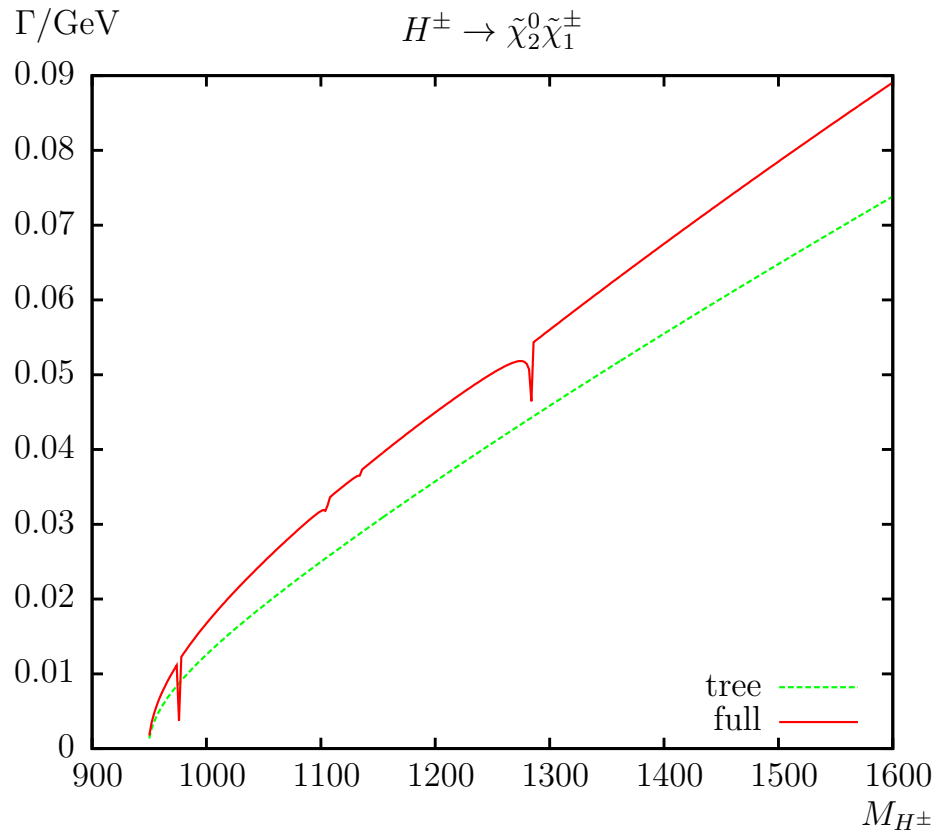
$\Rightarrow$  strong dependence on  $|M_1|, \mu$

# Heavy Higgs decay to heavier neutralinos:



- ⇒ loop corrections up to  $\sim 20\%$
- ⇒ strong phase dependence
- ⇒ level crossing, thresholds, ...

## Charged Higgs decay:



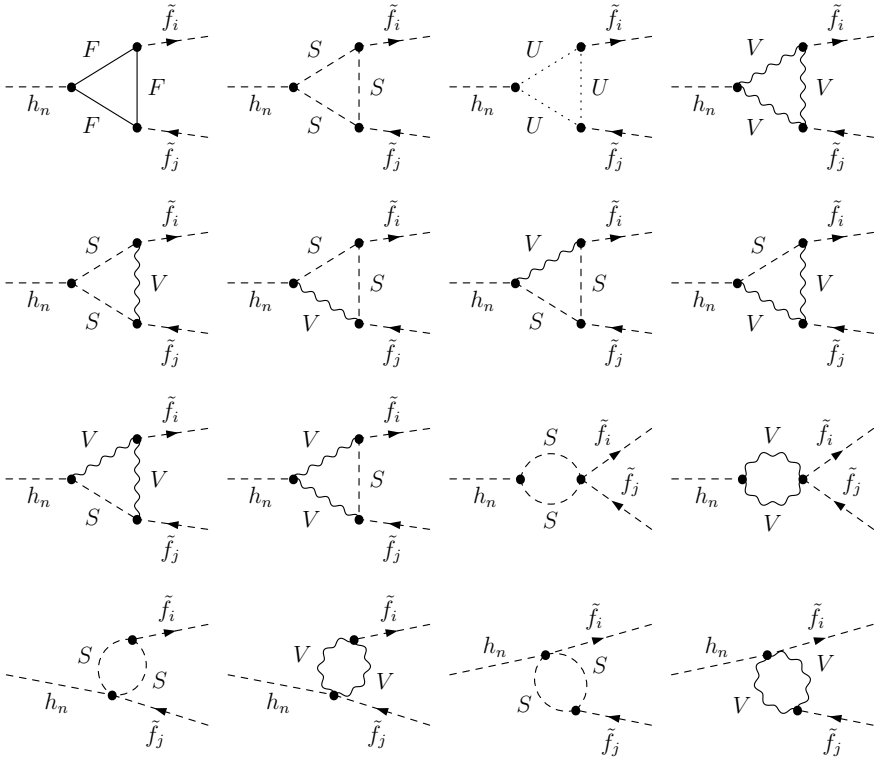
- ⇒ loop corrections up to  $\sim 20\%$
- ⇒ strong phase dependence
- ⇒ small difference between  $H^+$  and  $H^-$  decay

# 3. Higgs decays to sfermions

[arXiv:1410.2787]

$$\Gamma(h_n \rightarrow \tilde{f}_i \tilde{f}_j^\dagger) \quad (n = 2, 3; i, j = 1, 2)$$

$$\Gamma(H^\pm \rightarrow \tilde{f}_i \tilde{f}_j'^\dagger) \quad (i, j = 1, 2)$$



## Numerical example scenario:

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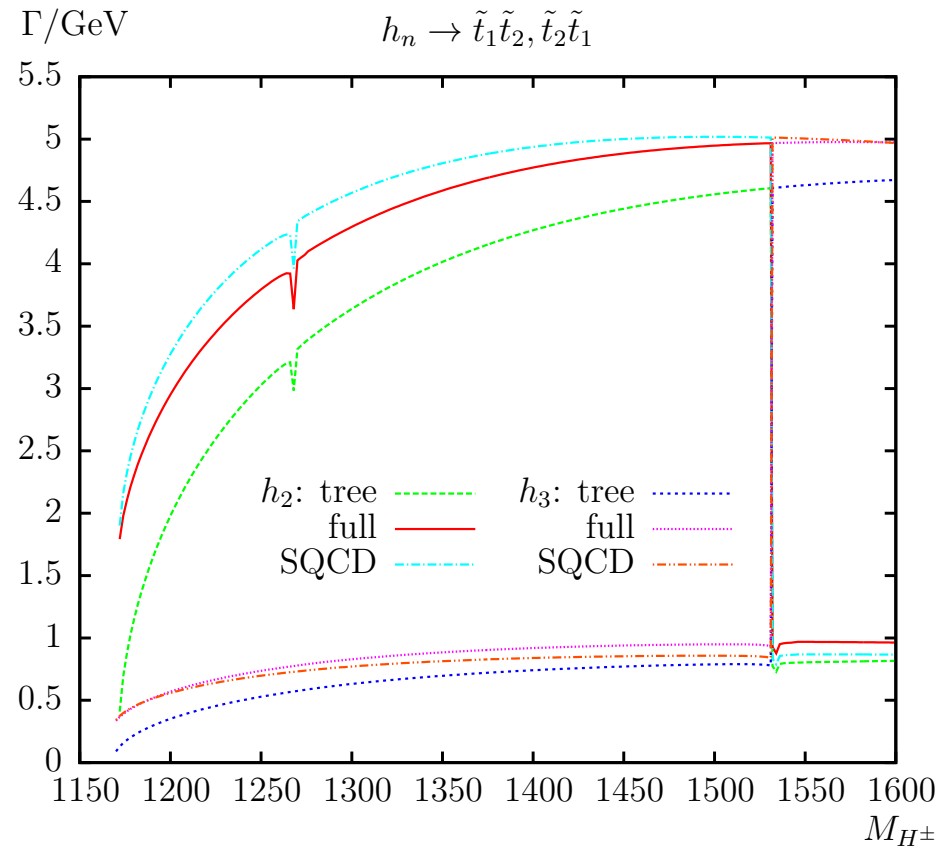
$\tan \beta$	$\mu$	$ A_t $	$ A_b $	$ A_\tau $	$M_1$	$M_2$	$M_3$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_2}$	$m_{\tilde{\nu}_\tau}$	$m_{\tilde{\tau}_2}$
10	500	1200	600	1000	300	600	1500	394	771	582	280	309

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Parameters varied:  $M_{H^\pm}$ ,  $\phi_{A_t}$ ,  $\phi_{A_b}$ ,  $\phi_{A_\tau}$

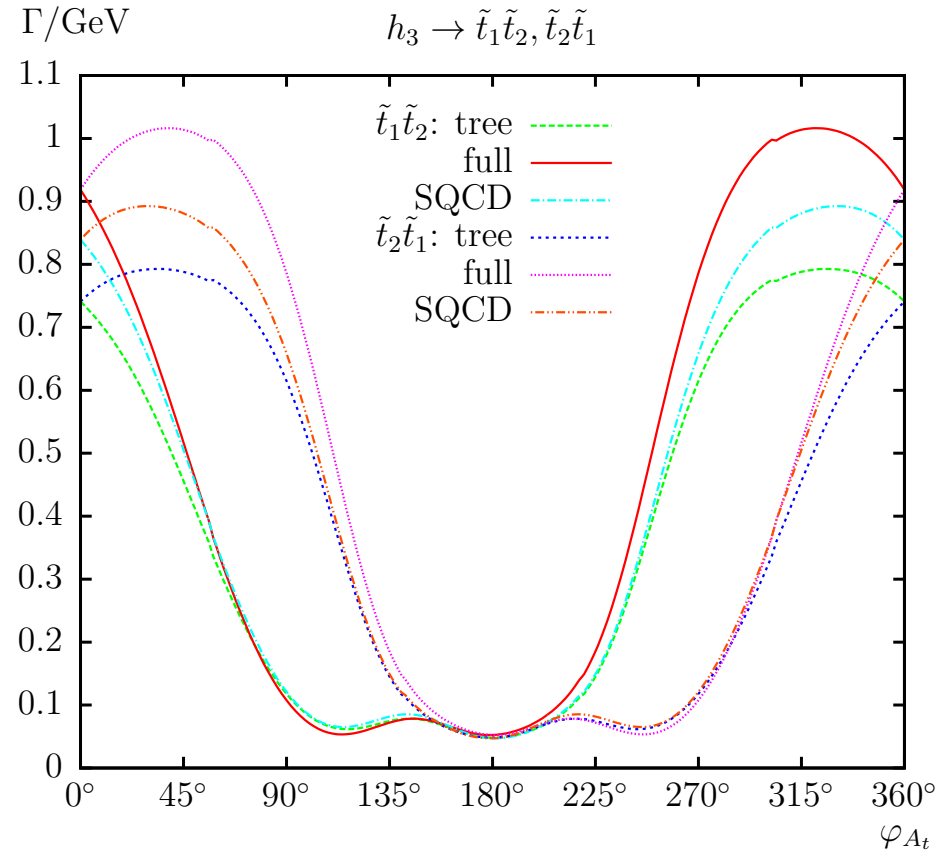
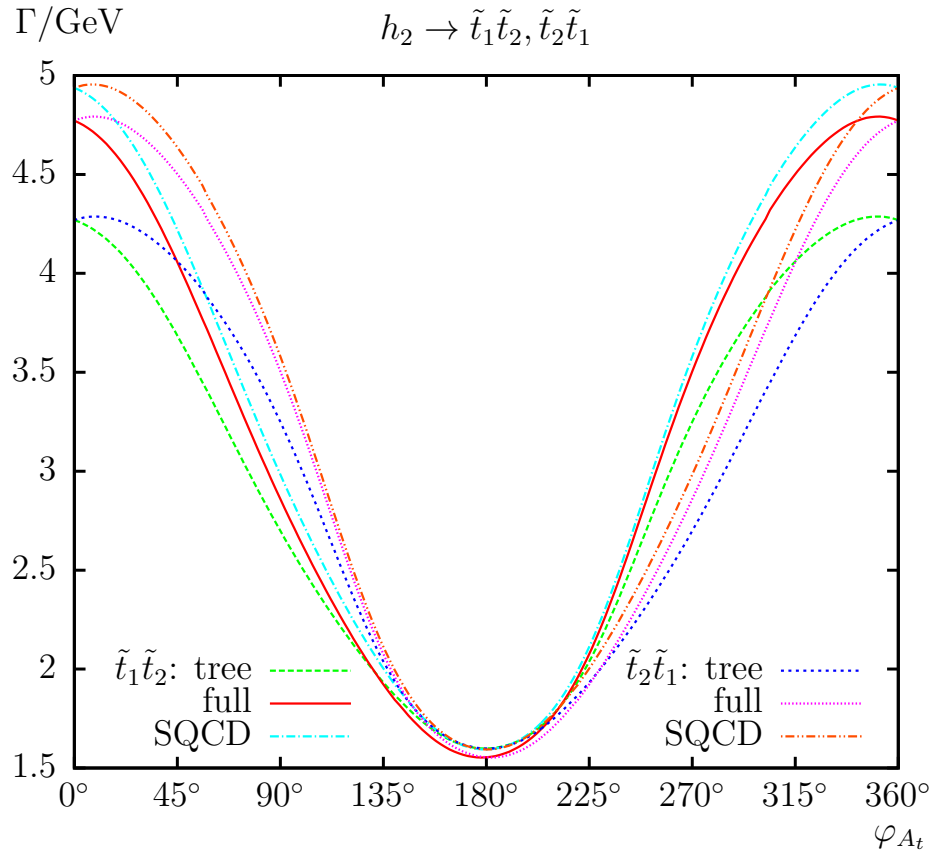
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- opens up many (all) decay channels
- relevant parameters varied
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## Heavy Higgs decay to stops:



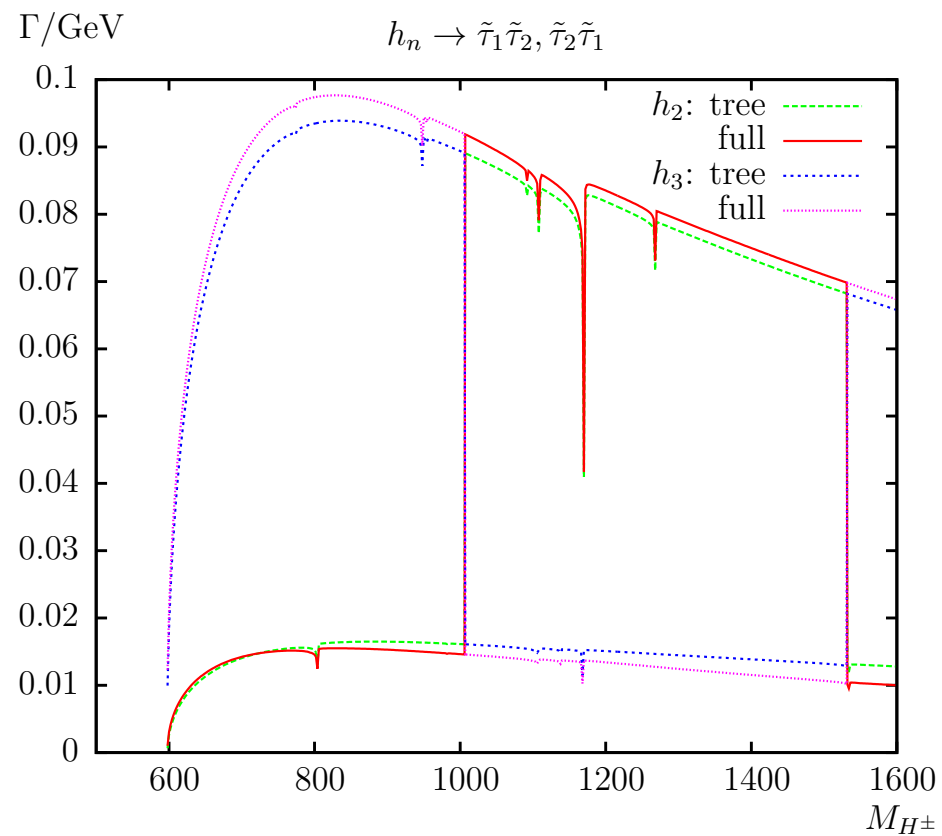
- ⇒ loop corrections up to  $\sim 30\%$
- ⇒ SUSY QCD not sufficient
- ⇒ level crossing, thresholds, ...

## Heavy Higgs decay to stops:



- ⇒ loop corrections up to  $\sim 30\%$ , SUSY EW important
- ⇒ strong phase dependence
- ⇒ difference between charge conjugated decays

## Heavy Higgs decay to staus:

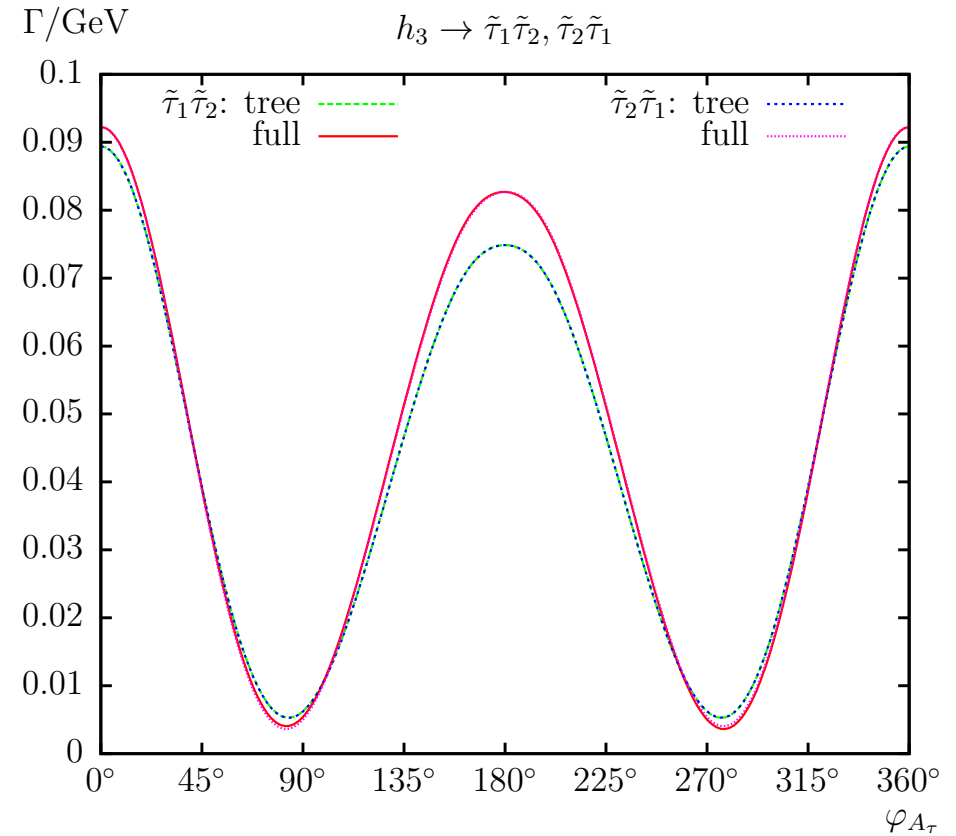
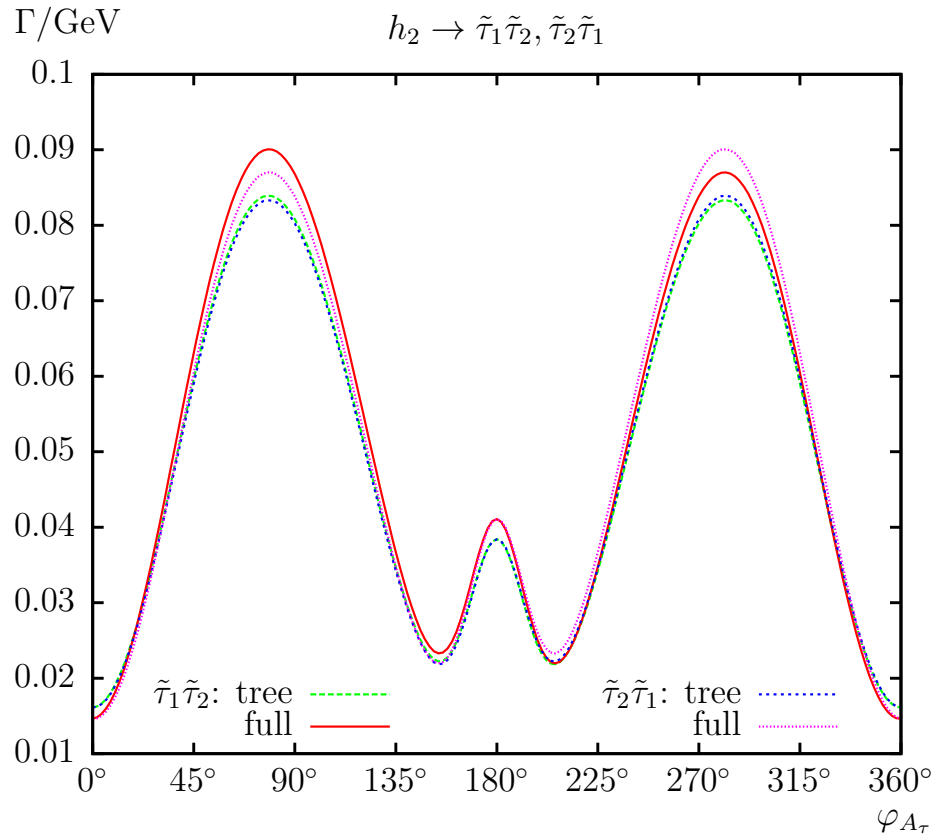


⇒ loop corrections up to  $\sim 10\%$ , purely EW

⇒ level crossing, thresholds, ...

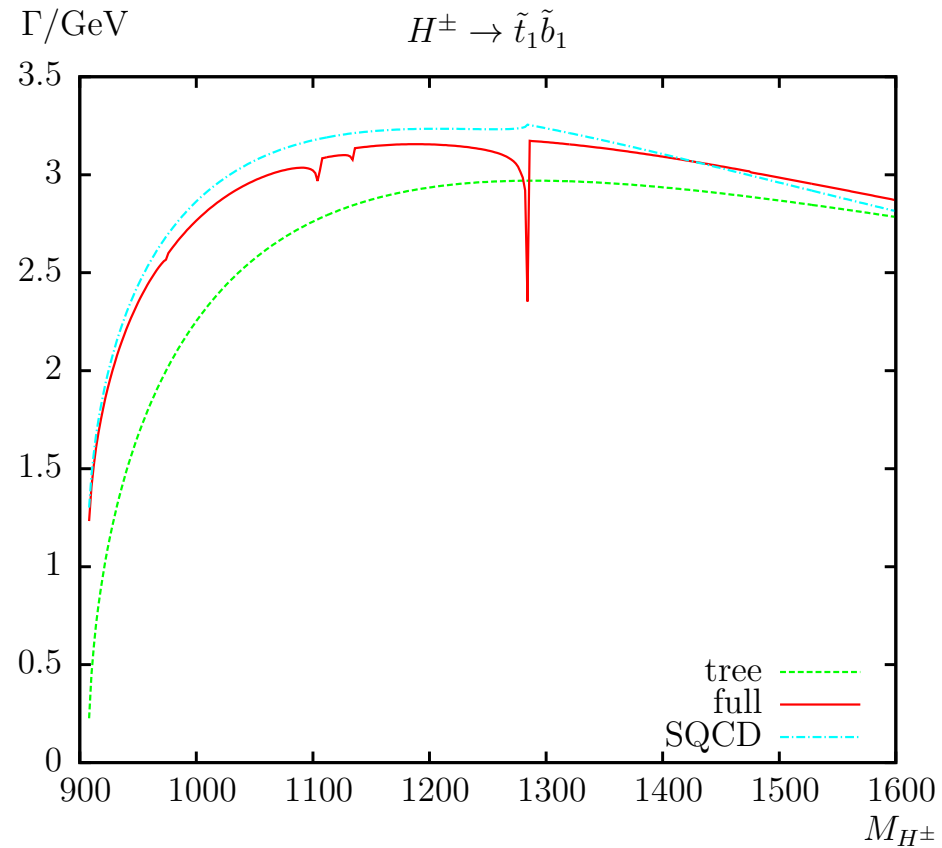


## Heavy Higgs decay to staus:



- ⇒ loop corrections up to  $\sim 10\%$ , purely EW
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- ⇒ small difference between charge conjugated decays

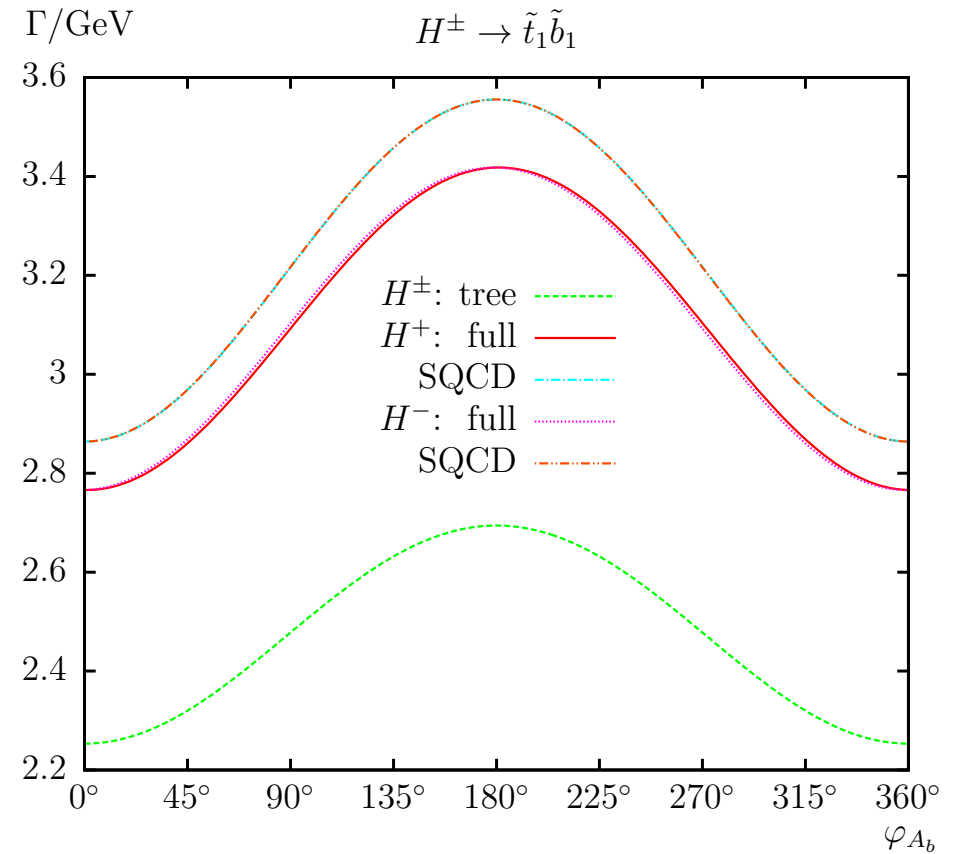
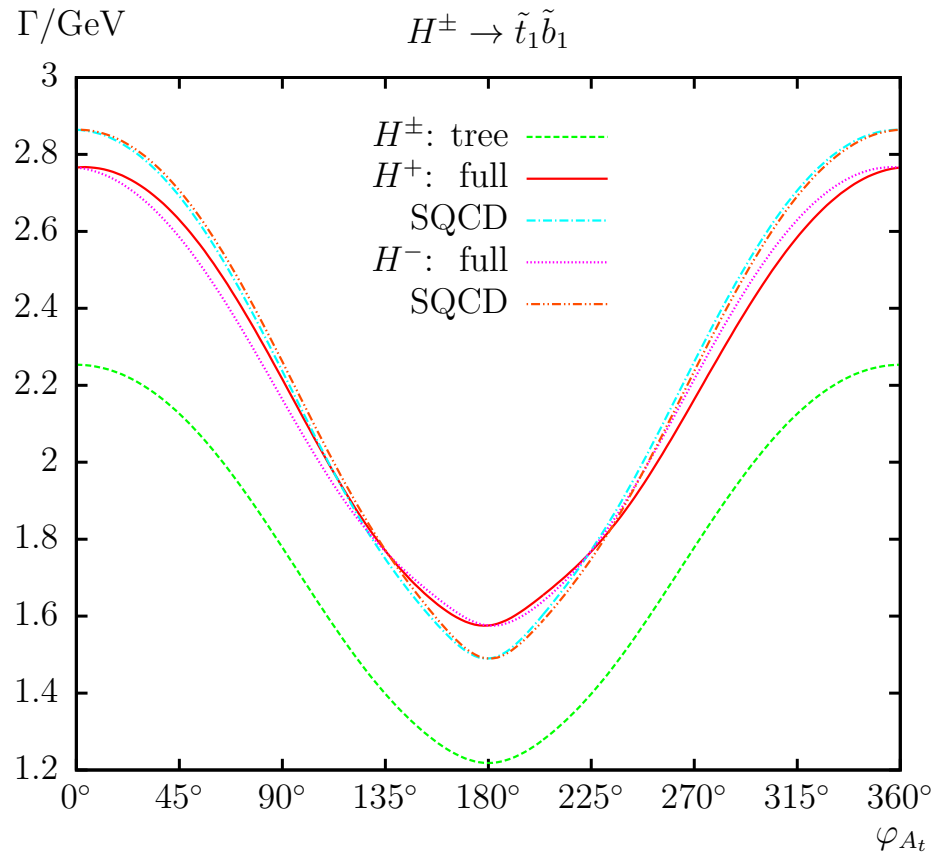
## Charged Higgs decay to stop/sbottom:



⇒ loop corrections up to  $\sim 30\%$

⇒ SUSY QCD not sufficient

## Charged Higgs decay to stop/sbottom:



- $\Rightarrow$  loop corrections up to  $\sim 30\%$ , SUSY EW important
- $\Rightarrow$  strong phase dependence
- $\Rightarrow$  small difference between charge conjugated decays

## 4. Conclusinos

- Loop corrections in BSM models are clearly important now
- **MSSM: renormalization** is still a (the) big(gest) issue
- **FeynArts, FormCalc**: model file **incl. complex renormalization** ready (one-loop, thoroughly tested!)
- Calculated:  
decays of Higgs to charginos/neutralinos and to sfermions including **complex phases** (+ hard/soft QED/QCD, ...)  
⇒ **corrections relevant for LHC/ILC**
- Examples shown:
  - **Light Higgs decay to Dark Matter**:  
correction up to  $\sim 20\%$ , strong phase dependence
  - **Heavy Higgs decays to charginos/neutralinos**:  
correction up to  $\sim 20\%$ , strong phase dependence
  - **Heavy Higgs decay to squarks/sleptons**:  
corrections up to  $\sim 30\%$ , SUSY QCD not sufficient



# Higgs Days at Santander 2015

## Theory meets Experiment

### 14.-18. September

contact: [Sven.Heinemeyer@cern.ch](mailto:Sven.Heinemeyer@cern.ch)

<http://www.ifca.es/HDays15>



Back-up